Muon Detection and Position Determination

A thesis submitted in partial fulfillment of the requirement
for the degree of Bachelor of Science in Physics
from the College of William and Mary in Virginia,

by

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Abstract

Experiment E160 at the Stanford Linear Accelerator Center will determine the A-dependence of J/ψ photoproduction. The J/ψ is reconstructed from $\mu^+ \mu^-$ pairs. Trajectories of these muons are found using horizontal and vertical arrays of scintillator hodoscopes. We will determine how accurately the muon's position along the length of the scintillator can be established through measurements of the difference in time and intensity of the signals produced by a photomultiplier tube on each end of a scintillator. This will allow one plane of scintillators to measure both horizontal and vertical muon positions.

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Contents

1 Introduction

The purpose of experiment E160 at SLAC is to observe the QCD dynamics of charmonium production and to deduce the J/ψ-nucleon cross section. The J/ψ particle is a spin 1 meson consisting of a charm and an anti-charm quark. To produce the J/ψ, photons are used since a photon can fluctuate into a virtual charm and anti-charm quark pair, which when incident upon nuclear matter, may develop into a J/ψ particle. The E160 experiment at the Stanford Linear Accelerator Center will determine the rate of J/ψ photoproduction for various nuclear targets. For the E160 experiment beryllium, aluminum, copper, and lead targets will be used. The characteristics of these elements are given in Table 1:

element	Z	A	ρ (g/cm^3)	g/cm^2	cm	rad. lengths	int. lengths	b^{-1}
Be	4	9.012	1.848	3.26	1.764	0.050	0.043	1.96
Al	13	26.980	2.700	3.36	1.245	0.140	0.032	2.02
Cu	29	63.546	8.960	2.57	0.287	0.200	0.019	1.55
Pb	82	207.200	11.350	1.27	0.112	0.200	0.007	0.77

Table 1: Characteristics of the four elements being used as targets in the E160 experiment

The average number of nucleons, designated by, *A*, is of the most importance. As can be seen, the *A* values spread over a large range.

The photons needed for the experiment are produced through bremsstrahlung. For this, the 50 GeV electrons produced by SLAC are directed through a thin diamond target. The charge of the nucleus then decelerates the electron, which causes it to radiate [1]. Coherent photons are produced in the crystal lattice, which gives a quasi-mono-energetic beam of photons. The photons then are directed to a metalic target, in which the J/ψ particles are produced.

Although the J/ψ has a relatively large mass of 3096.9 MeV, it cannot be detected directly due to its short lifetime, which is on the order of 10^{-20} seconds. For this reason the J/ψ must be studied indirectly through the resultant particles it produces; 6% of the time the J/ψ will decay into a muon pair, which is measured in a spectrometer containing several planes of detectors, as shown in Figure 1.

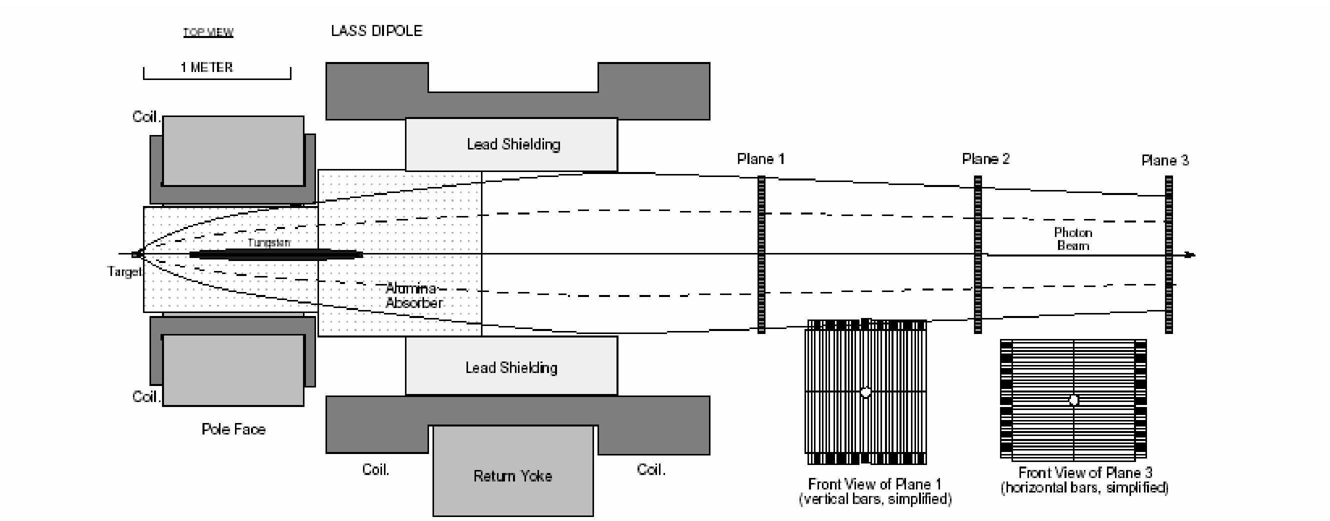


Figure 1: Spectrometer design for the SLAC E160 experiment

Two dipole magnets with the same polarity are used to analyze the muons' momenta. Representative trajectories of the muons are shown by the solid and dashed lines in Figure 1. In order to detect hundreds of ψ mesons per day, the detectors have to be able to distinguish muons from a large background of hadronics. To do this Al_2O_3 absorbers are used, which are placed directly downstream from the target. Since the mass of the muon, about .1 GeV, is approximately two hundred times that of the electron, muons are not stopped as readily as electrons are as they travel through the Al_2O_3. The muons interact only electromagnetically in the Al_2O_3 target with only a small decrease in energy, whereas pions and kaons are stopped in the absorber [2]. Planes of scintillator hodoscopes are connected to multi-hit TDC's in order to detect the muons. As seen in Figure 1 at least one plane will have scintillator fingers that are arranged along the vertical, and the same is true for the horizontal. Two sub-planes of scintillators with fingers of 1.5cm in width are arranged in order to give a resolution of 0.15 cm for detecting muons along the horizontal. For detection along the vertical a single sub-plane of scintillators with a width of 2 cm are used, giving a position resolution of 0.7 cm. From these detections, the trajectories of the muons can be determined and in turn, the original J/ψ's energy and momentum can be found.

2 Detector Design

2.1 Description of Scinitillators

As stated in Section 1, to detect muons from the decay of the J/ψ, planes of scintillators are used. For the third plane of scintillator fingers, a photomultiplier tube is placed at each end. A signal is produced by an incident muon that will excite the scintillator. The excited material will then decay to its ground state. In doing this, light is emitted, which then travels down the length of the scintillator by a series of internal reflections. The light is collected by a photomultiplier tube that registers by a process that will be described later on.

G_{En} Neutron Detectors [3] from the University of Virginia will be stacked to form the muon detector. For the tests at the College of William and Mary, only two such detectors are used. The scintillator portion of the detector is of the dimensions 1.6m by 10cm by 10cm, with light pipes and phototubes present at either end as seen in Figure 2:

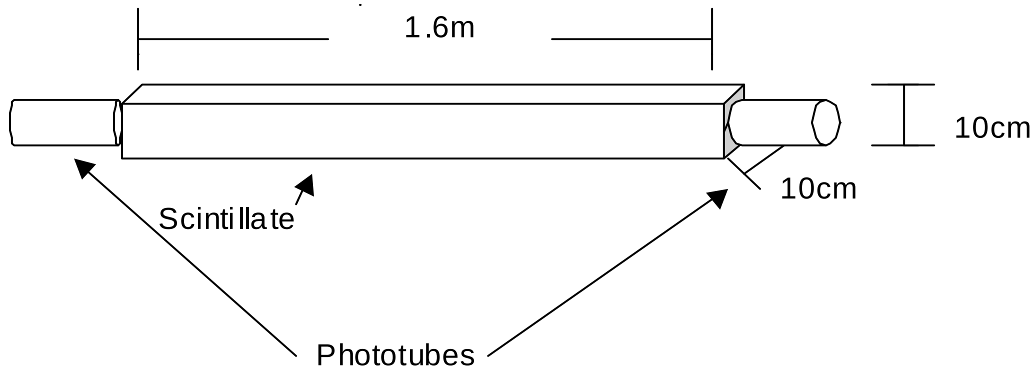


Figure 2: Scintillator and Phototube

The scintillating material is Bicron 408, which has an index of refraction of 1.58. The density of the plastic is 1.032 g/cm^3, with a bulk attenuation length of 380 cm. The material's rise and decay times are 0.9 and 2.1, respectively, in nanoseconds [3]. When these detectors are stacked as a series of scintillator planes, they can be used as a time of flight (TOF) counter.

2.2 Photomultiplier Tubes

The Photomultiplier tubes create a large signal from each photon using the photoelectric effect. A single photon incident on the photocathode, releases one electron. The electron is drawn away from the photocathode by an applied voltage toward the first of several dynodes. As the electron travels it is accelerated until it strikes the dynode, producing secondary electrons. This process is repeated for each dynode that is present.

If *d* electrons are released at each dynode and *n* dynodes are present, the total number of electrons produced, *N*, is

$$N = d^n \tag{1}$$

A threshold voltage can be established for anode signals by the use of a discriminator. The higher the threshold, the large the signal must be in order to produce a logic pulse. Any noise coming from the photomultiplier tube can be limited by increasing the threshold voltage, as long as the noise is not too large. For this reason, it is expected that as the threshold is raised in the range of low voltages, the count rate of events will decrease. This can be seen in Figure 3, in which a small scintiallator's threshold was changed and the number of counts recorded.

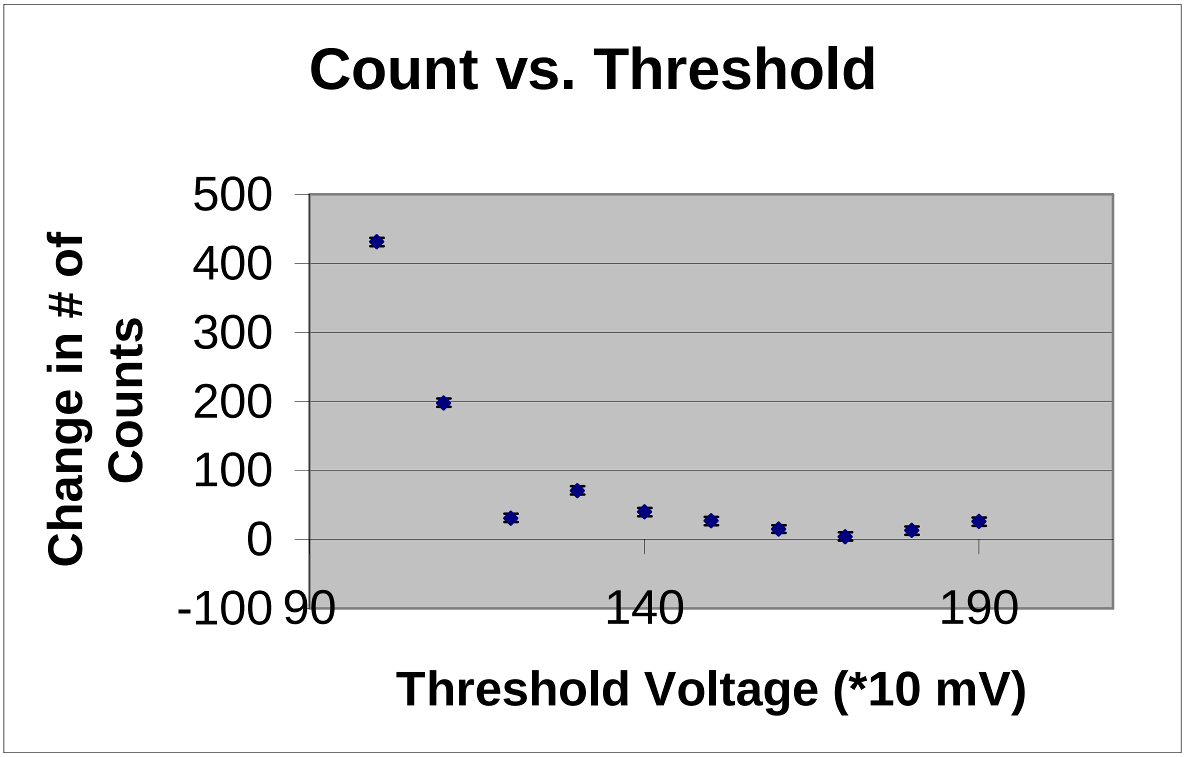


Figure 3: The change in the number of counts as the threshold voltage of the discriminator is increased. The large change for low voltages represents a large amount of noise being recorded.

The desired threshold setting will be one in which most of the noise will be rejected, while still counting all muon signals. Any noise still present can be further reduced by requiring a coincidence between two scintillators aligned such that a particle can travel through both. The width of the resulting logic signal considered can be adjusted. This width should be set to minimize a coinicidence count with noise while retaining a difference in time necessary for the two detectors to create a signal of actual muons. For this experiment the PMT's will be set to a voltage on the order of 1900V.

3 Cosmic Muons

The measurements described in Section 2 will be accomplished by the use of cosmic muons. Muons of this nature are mostly produced high in the atmosphere, only to then travel to sea level where they are detected. For this reason, their angular distribution is a function of energy loss from travel through the atmosphere and decay. Most muons have a decay length of 15 km when they are formed in the upper atmosphere, but this is reduced to under 9 km due to energy loss. Because of these effects, the average angular distribution at ground level is of the form:

$$N(\theta) = \alpha \cos^2 \theta \qquad (7)$$

where N is the number of muons detected for a given angle with respect to the vertical. The average intensity of vertical muons above 1 GeV/c at sea level have been found to be on the order of 70 $m^{-2}s^{-1}sr^{-1}$ as seen in Figure 4 [4].

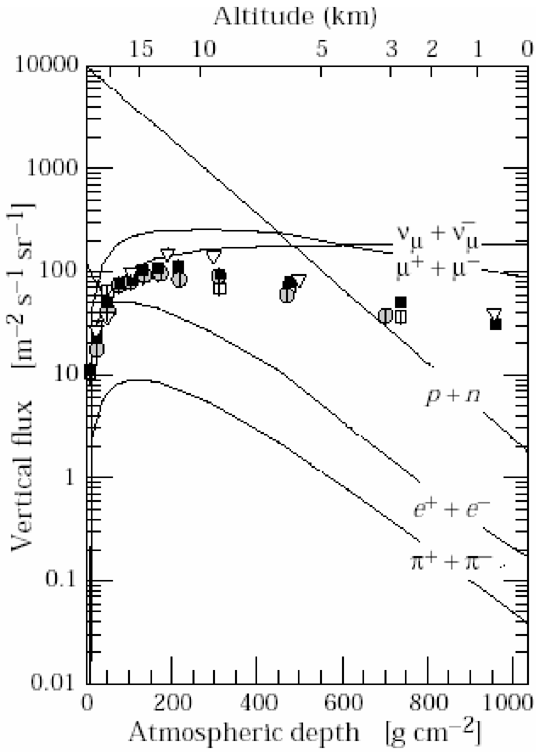


Figure 4: Graph of the vertical fluxes of muons, as well as other cosmic rays, which have E > 1 GeV in the atmosphere as a function of depth [4].

4 Detector and DAQ System Setup

The photomultiplier tubes connected to the scintillators are powered using the 64-channel CAEN SY403 system high voltage supply. Once a signal is registered by the photomultiplier tubes, the output is converted from a simple voltage spike to a logic signal that can be observed and recorded in the data acquisition system (DAQ). Three separate modules: a QDC, charge-to-digital converter; a TDC, time-to-digital converter; and a scalar module are used to create the appropriate data signals. Using a VME crate, the modules are connected to the DAQ system.

The output signal of the photomultiplier tubes consist of a simple voltage spike, in order to use the time, charge and scalar modules, the signal must first be changed into a logic pulse. The following is a schematic of the modules and their setup for the experiment:

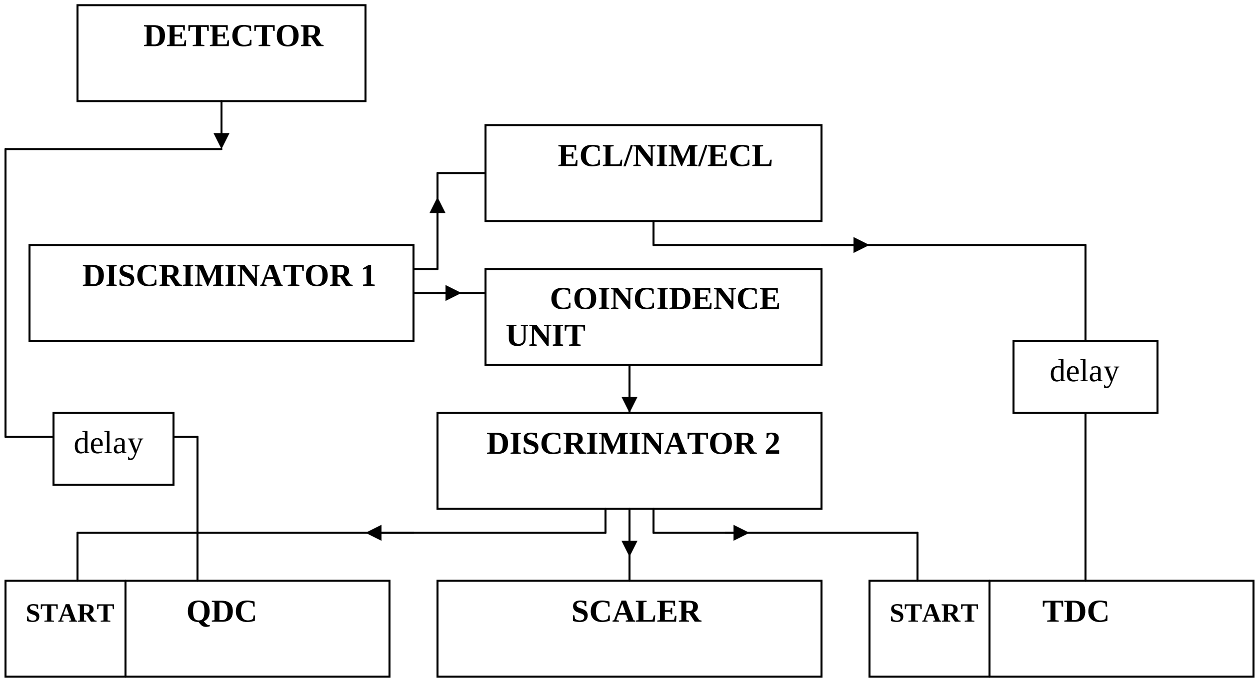


Figure 5: Detector and logic system schematic

From the PMT, the voltage spike is sent to a LeCroy 428F Quad Linear Fan-in/Fan-out module. The fan-out then splits the pulse, sending one signal to the multiple logic modules, which create a COM logic signal, and allow the pulse to be changed to a logic signal that can be sent to the scalar and the TDC. The other signal from the 428F is sent to the QDC. It is delayed however, in order to allow it to be received after the COM logic pulse arrives at the gate. NIM signals were used, while the QDC accepts only emitter-coupled logic signals. From the NIM, the pulse was sent through a BNC cable, which was in turn connected to the cable input of the QDC.

A LeCroy 4616 ECL-NIM-ECL module was used to convert the NIM signals to the ECL signals required as an input for the TDC. For the other signal from the fan-out module, a LeCroy 4616 coincidence unit is used, which performs a logic AND of the signals. Each signal is set to be approximately 50 ns in length, and if all four signals are registered within that time limit, a signal is sent from the coincidence unit. The AND signal is then sent to a Phillips 711 leading edge discriminator and from there to the time, charge, and scalar converters.

5 Determining Muon's Position

5.1 Needed Equations

Both timing into motion and pulse-heights received from th scintillators will be used to find the muon's position along the length of the scintillator. We first consider the difference in time required for emitted light to reach either side of the detector. Suppose the scintillator is of length L, time of detection for one phototube is $t_{,1}$ and for the other $t_{2:}$

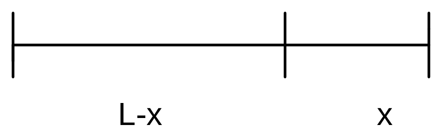


Figure 6: Distance from either end of scintillator for a given muon

To reach the PMT on the left side of the detector, the photon must travel the length *L-x*, and to reach the right side, the photon must travel a distance *x*. Therefore the following equations hold:

$$t_2 = t_0 + \frac{L - x}{V} \quad (2)$$

$$t_1 = t_0 + \frac{x}{V} \quad (3)$$

$$t_1 - t_2 = \frac{-L + 2x}{V} \quad (4)$$

,where V is the transit velocity of the photon in the scintillator, and x runs along the length of the scintillator. If one then solves for x, the position of the muon can be determine using the following:

$$x = \frac{V}{2}(t_2 - t_1) + \frac{L}{2} \qquad (5)$$

This is a linear function of the difference in signal times. The distance traveled by a photon in the scintillator depends also on the angle by which it travels with respect to the length of the scintillator. A light traveling at a larger angle with respect to the axis along the length of the scintillator requires a longer distance in order to reach the end and be registered by the phototube. Therefore a correction must be made to the measured distance traveled in order to calculate a valid result of the position as a function of the signals' time difference. The shortest distance traveled would correspond to a photon with a trajectory angle of zero, and the greatest distance will be of a muon traveling with the largest angle of complete reflection, which is a property of the scintillating material alone. The average of the zero and maximum angle of reflection will therefore give the average distance traveled by the photons produced by a single muon.

The intensity of the signals can also be observed, and is found to drop of exponentially by the equation:

$$I = I_0 e^{-(\frac{x}{L_0})} \qquad (6)$$

where I_0 and L_0 are constants determined by the scintalltor. If the signal size in one detector is denoted I_1 and the signal size in the other I_2, then the following equations hold:

$$I_1 = I_0 e^{-(\frac{x}{L_0})} \qquad (7)$$

$$I_2 = I_0 e^{-(\frac{L-x}{L_0})} \tag{8}$$

and by dividing Eq. 7 by Eq. 8, the following equation is found:

$$\frac{2x}{L_0} = -\ln\left(\frac{I_1}{I_2}\right) + \frac{L}{L_0} \tag{9}$$

As seen in Eq. 9, the position can be determined by a function of the natural log of the intensity ratios.

5.2 Data

A data set of 10,000 events is taken and stored using the DAQ system. The Physics Analysis Workstation (PAW) is then used to create histograms and scatter plots of the events. The following histogram is an example of such:

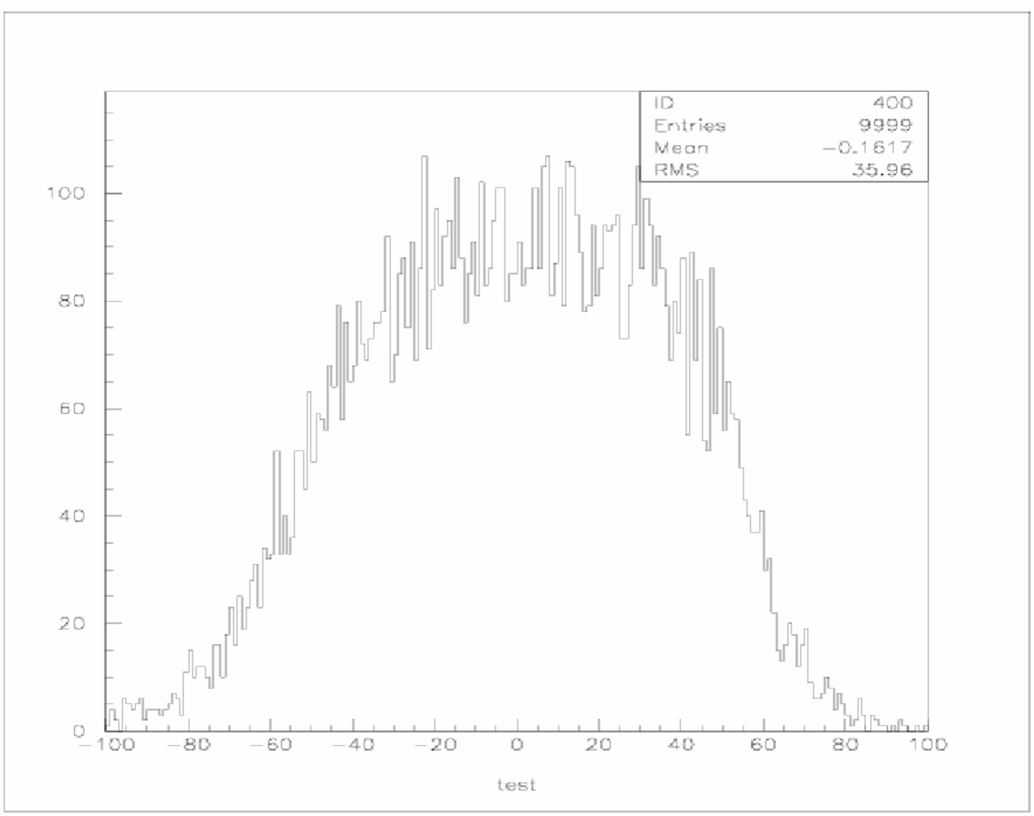


Figure 6: Histogram of events as the natural log of the ratio of intensity (QDC) signals

The histogram is a representation of Equation 9, which is the ratio of the two QDC signals at either end of one of the detectors. The distribution is as expected since the count of the ratio is reasonably continous over the length of the detector, and drops off at either end. The data is scaled so that each unit along the x-axis of the histogram is one centimeter. Similar histograms are formed for the other set of QDC's and for the difference in TDC readings.

A scatter plot of TDC3-TDC2 versus TDC1-TDC1 can also be analyzed, this is shown in Figure 7:

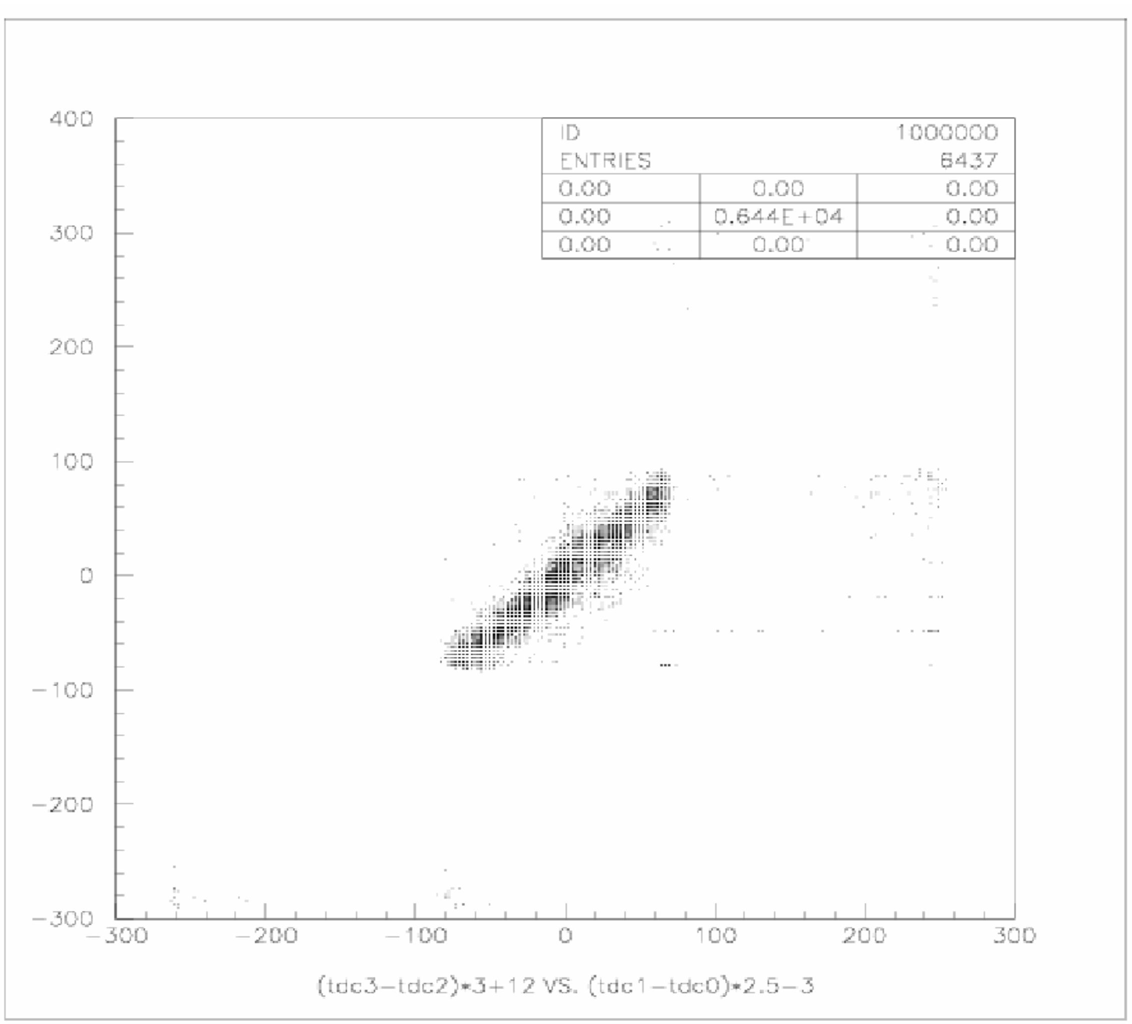
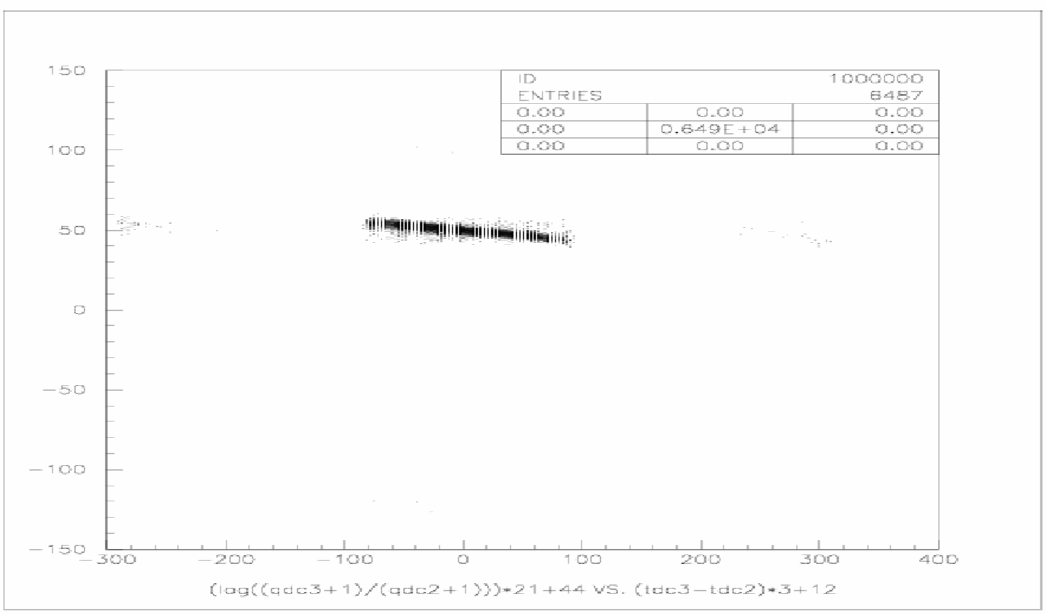


Figure 7: Scatter plot of the difference in TDC3 and TDC2
versus the difference in TDC1 and TDC0

The scatter plot shows a linear coralation between the differences in two of the TDC readings versus the other two. The x-axis of the graph represents the difference in time between TDC3 and TDC2, while the y-axis represents the difference inTDC1 and TDC0. Therefore, point on the lower left of the distribution represent muons that reached PMT #2 and PMT #0 first, and points in the upper right of the distribution are those that reached PMT #3 and PMT #1 first. The correlation observed is as would be expected since a large difference in TDC3 and TDC2, would also bring about a large difference in TDC1 and TDC0. This is because a muon that passes through one side of the first detector would also pass through the same side of the second.

To determine the position using both the QDC's and the TDC's, a scatter plot can be used which will plot the ratio of the natural log of the QDC values versus the difference in the TDC values.

Figure 7: Scatter plot of the ratio of the natural log of QDC3 and QDC2



versus the difference in TDC3 and TDC2

The values of each axis have been scaled so that each unit of the x-axis represents a centimeter. The length of the cluster of points is therefore proportional to 160 cm, the length of the scintillator. Using this proportion and measuring the width of the cluster of points, the error in the position measurement can be found. The width for this plot is found to be 16 cm in length. Therefore, the predicted error the position measurement using both time and attenuation of the signals gives an error of about 16 cm.

6 Conclusion

The detection system and the electronics involved have shown that cosmic muons can be detected and there position determined to some degree of accuracy. From the data observed, it is clear that a coincidence between the two detectors removed much of the noise present. Through the determining the attenuation and time difference in the signals produced by each PMT, a position measurement can be made within an length of 16 cm. This error is small enough, so that if these measurements were preformed by the third plane of SLAC E160 scintillators, the muons trajectories would be able to be determined with a greater accuracy.

[1] Knoll, Glenn F. Radiation Detection and Measurement, John Wiley & Sons, New York 2000.

[2] Ghazikhanian, et al. Proposal to Measure the A-Dependence of J/ψ and ψ' Photoproduction E160 Experiment, 2000. www.slacstanford.edu/exp/e160/jpsi.pdf

[3] Day, Donal "G_{En} Neutron Detector – A Collection of information". Jlab internal document September 2000

[4] Zhu, Hong Guo, PhD Thesis U.Va 2000, Cosmic Background Radiation.